



The Influence of moisture- and load variations on the fatigue behaviour of wood

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Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

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Citation (APA):
Nielsen, L. F. (2005). *The Influence of moisture- and load variations on the fatigue behaviour of wood*. BYG Sagsrapport No. SR 05-09

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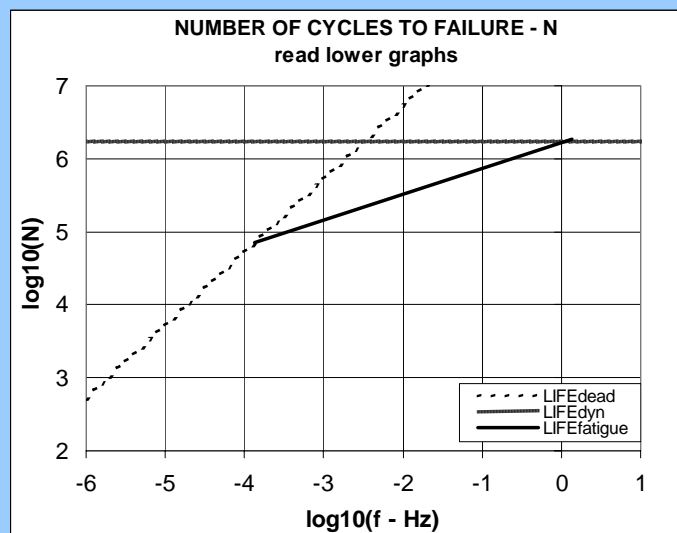
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The influence of moisture- and load variations on the fatigue behavior of wood

Lauge Fuglsang Nielsen



Predicted number of load cycles to fatigue failure. Wood quality, $FL = 0.25$. Variable load level, $SL = 0 - 50\%$. Variable surface moisture content, $u_s = 11\% - 20\%$.

**Modellering af fugt- og lastvariationers betydning
for træes mekaniske egenskaber**

Det Strategiske Forskningsråds Materialeprogram

DSF:2020-00-0017

**The influence of moisture- and load variations
on the fatigue behavior of wood**

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The influence of moisture- and load variations on the fatigue behavior of wood

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Abstract: It is demonstrated in this paper that the influence of moisture- and load variations on lifetime and residual strength (re-cycle strength) of wood can be considered by theories previously developed by the author. The common, controlling factor is creep, which can be modified very easily by introducing a special moisture dependent relaxation time in the well-known Power-Law creep expression.

Because basic failure mechanisms in wood are invariant with respect to loading modes, it is suggested that a number of methods used in design of wood structures can be generalized/simplified to apply irrespective of loading modes and moisture conditions. Reliability studies may become more ‘reliable’ as the result of recognizing property distributions to be related.

Keywords: Moisture variation, load variation, Power-Law creep, lifetime, fatigue, residual strength (re-cycle strength).

1. INTRODUCTION

The intension of this paper is to simplify the models used in practical design of wood structures. The models should be based on the fewest possible real basic mechanical parameters for classification of (damage) structure and viscoelasticity.

The specific examples considered in this paper is lifetime of wood as influenced by moisture- and load variations. It is demonstrated in this paper that lifetime under these actions can be considered by the same damage mechanisms, which have been established previously for constant moisture conditions, see [1]. We do not need two different failure mechanisms. One is enough: Damages expand in a solid, the viscoelastic properties of which changes because of moisture variations.

The format of the paper presented is that of an operational summary of property predictions made by the author’s DVM-theory (Damaged Viscoelastic Material) presented/developed in [1,2,3]. (Recently the most important prediction formulas have been summarized in [4]). The text of the paper is rather brief. Only very few theoretical explanations are presented. Such must be studied in the original papers just mentioned and in some further references listed at the end of the paper. The list of symbols – also at the end of the paper – should be frequently consulted.

1.1 Material properties

Creep

The viscoelastic behavior of wood can be very well described by the so-called Power-Law (normalized) creep expression presented in Equation 1. The expression is quantified by the constant creep power b (of magnitude $1/3 - 1/5$) - and the relaxation time τ , which depends on a homogeneously distributed moisture content of $u(\%)$ as indicated. Time is denoted by t .

$$C = 1 + \left(\frac{t}{\tau} \right)^b \quad \text{with relaxation time } \tau = \tau_{15} * 10^{(15-u)/10} \quad \text{where} \quad (1)$$

$$\tau_{15} \approx \begin{cases} 10^4 - 10^5 \text{ days for bulk creep} \\ 10 \text{ days for creep in damaged areas, cracks} \end{cases} \quad \text{is relaxation time at } u = 15\%$$

Quality

Wood quality is defined as immediate strength, σ_{CR} , relative to theoretical strength, σ_L . We introduce the symbol, $FL = \sigma_{CR}/\sigma_L$, for strength level (or wood quality) which can be estimated from Figure 1.

Remark: It is noticed that strength levels analytically considered in this paper are $FL < 1/3$, which covers most wood in practice. For analysis of wood with higher strength levels a few modifications have to be introduced, see [4].

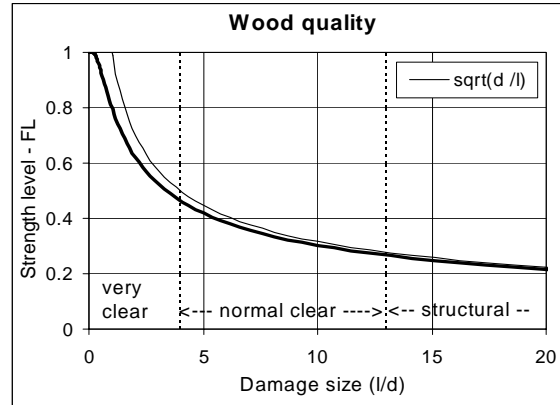


Figure 1. Wood quality estimated from damage size, l , relative to the damage nucleus (inherent defect) $d = 0.3 \text{ mm}$.

2. LIFETIME AT CONSTANT MOISTURE

Lifetime expressions for wood at constant moisture conditions are presented in the following sections. Symbols used are explained in the list of symbols at the end of this paper. Of special interest are the load level, $SL = \sigma/\sigma_{CR}$, which is load applied relative to strength. The symbol, κ , used is damage ratio, which is immediate (time dependent) damage size (ℓ) relative to its initial size (ℓ_0).

2.1 Constant load

At constant load, lifetime of wood can be predicted by the following Equation 2*, which expands as shown in Equation 3 for wood with special creep powers.

* The damage rate expression applies also for variable loads as long as positive rates are predicted.

$$\begin{aligned}
\frac{d\kappa}{dt} &= \frac{(\pi FL)^2}{8q\tau} \frac{\kappa SL^2}{[(\kappa SL^2)^{-1} - 1]^{1/b}} \quad \text{with } q = \left[\frac{(1+b)(2+b)}{2} \right]^{1/b} \quad (\text{damage rate}) \Rightarrow \\
\frac{t}{\tau} &= (1/SL^2 - 1)^{1/b} + \frac{8q}{\pi^2 FL^2 SL^2} \int_{1/(\kappa SL^2) - 1}^{1/SL^2 - 1} \frac{x^{1/b}}{1+x} dx \quad (\text{damage-time relation}) \\
\frac{t_{CAT}}{\tau} &= (1/SL^2 - 1)^{1/b} + \frac{8q}{\pi^2 FL^2 SL^2} \int_0^{1/SL^2 - 1} \frac{x^{1/b}}{1+x} dx \quad (\text{lifetime, where } \kappa = \kappa_{CR} = 1/SL^2)
\end{aligned} \tag{2}$$

$$\frac{t_{CAT}}{\tau} = \mu^{1/b} + \frac{I}{(FL * SL)^2} \begin{cases} 3.06 * \left[\frac{\mu^3}{3} - \frac{\mu^2}{2} + \mu - \log(\mu + 1) \right] & b = \frac{1}{3} \\ 3.17 * \left[\frac{\mu^4}{4} - \frac{\mu^3}{3} + \frac{\mu^2}{2} - \mu + \log(\mu + 1) \right] & b = \frac{1}{4} \\ 3.25 * \left[\frac{\mu^5}{5} - \frac{\mu^4}{4} + \frac{\mu^3}{3} - \frac{\mu^2}{2} + \mu - \log(\mu + 1) \right] & b = \frac{1}{5} \end{cases} \quad \text{with } \mu = \frac{I}{SL^2} - 1 \tag{3}$$

For κ expanding from 1 to the critical damage ratio $\kappa_{CR} = 1/SL^2$ the second term in Equation 2 can be used to determine residual strength (re-cycle strength), $S_R = \sigma_{CR}(t)/\sigma_{CR} = 1/\sqrt{\kappa}$

Important: We notice that all expressions are fully dimensionless with respect to strength, load, and time. Some results illustrating this feature are shown in Figures 2 and 3.

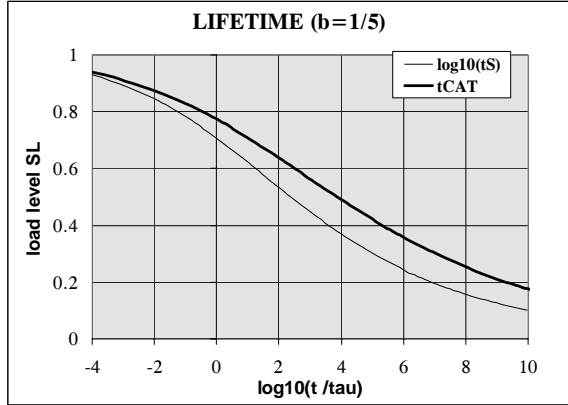


Figure 2. Non-dimensional prediction of lifetime for wood of quality, $FL = 0.25$.

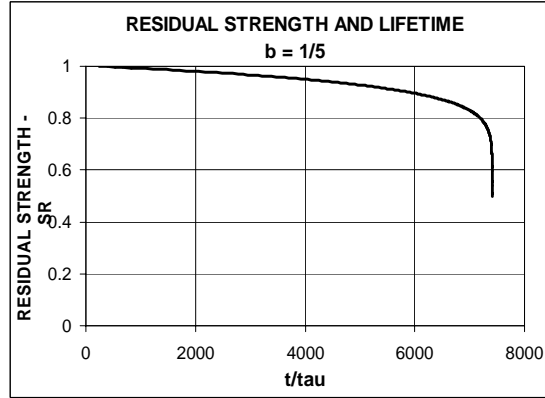


Figure 3. Non-dimensional prediction of residual strength for wood of quality $FL = 0.25$.

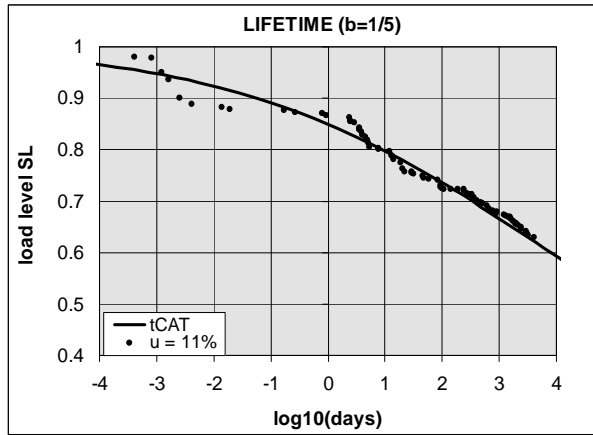


Figure 4. $FL = 0.25$, $\tau = 25.4$ days. $u \equiv 11\%$. Experimental data: P. Hoffmeyer [5,6].

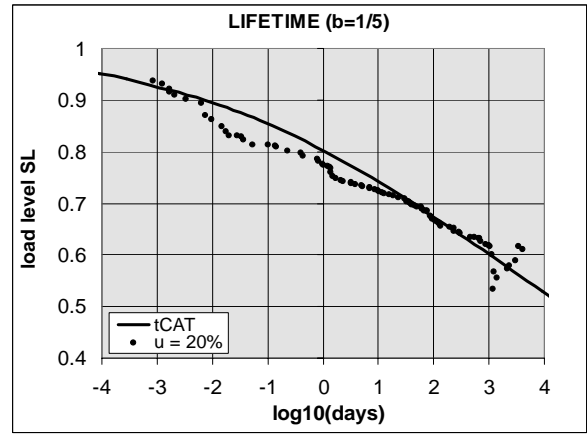


Figure 5. $FL = 0.25$, $\tau = 3.20$ days. $u \equiv 20\%$. Experimental data: P. Hoffmeyer [5,6].

Real results with real quantites of strength, load, and lifetime are compared in Figures 4 and 5

with experimental data obtained by Hoffmeyer in his work [5,6] on failure of wood as influenced by moisture and duration of load. The results of a residual strength analysis based on the Hoffmeyer moisture data ($u \equiv 20\%$), are presented in Figure 6.

2.2 Variable load (fatigue)

Lifetime solutions for wood subjected to harmonic loads are developed in [1] following the energy dissipation in damaged areas (cracks) as it develops with time. Two mechanisms are involved: A creep mechanism and a crack closure mechanism. Catastrophic failure occurs when the total dissipation becomes critical. Some results from the analysis in [1] are shown in Figures 8 - 11. The theory developed is strongly justified by various experiments – such as presented in Bach [7] and MacNatt [8,9] – see Figures 10 and 11.

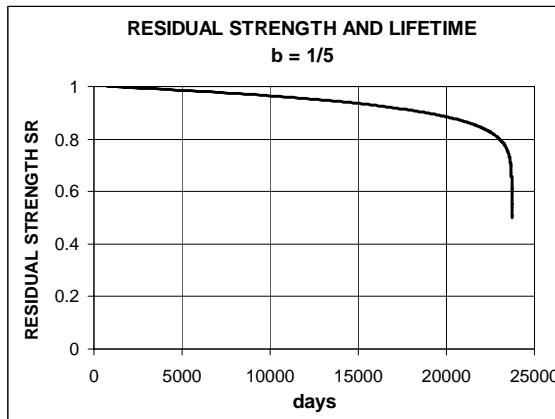


Figure 6. Residual strength for wood of quality $FL = 0.25$. Moisture content $u = 20\%$ ($\tau = 3.2$ days). Load is $SL = 0.5$

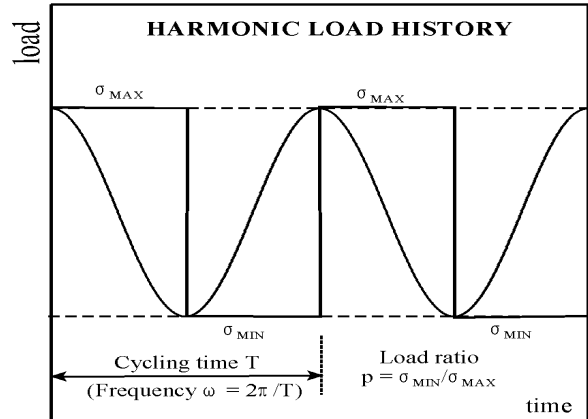


Figure 7. Variable load considered. (In analysis square wave load is assumed).

We notice that the, graphical, presentations shown in Figures 8 and 9 ($FL = 0.2$, $b = 0.2$), can be used for any wood quality and relaxation time (constant moisture content).

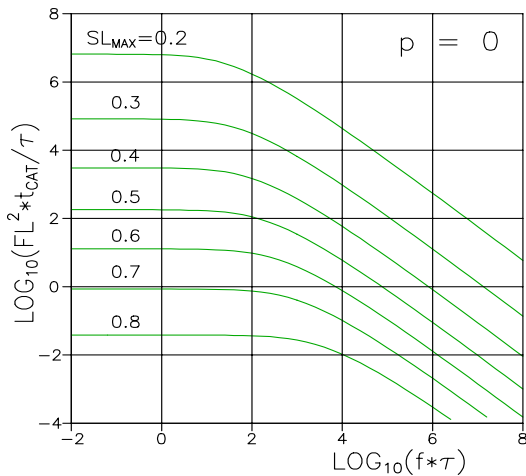


Figure 8. Normalized time to failure, accurate analysis with fatigue parameters $(C, M) = (3, 9)$

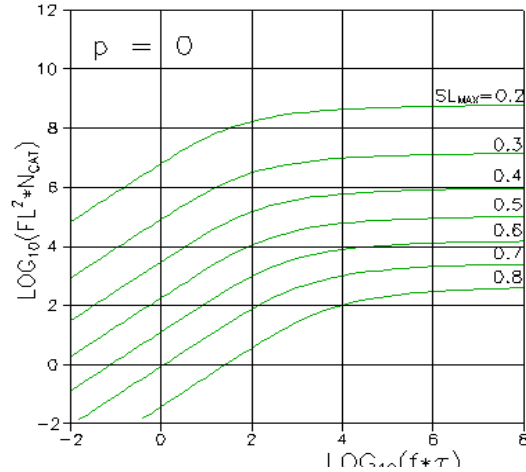


Figure 9. Number of load cycles to failure, accurate analysis with fatigue parameters $(C, M) = (3, 9)$.

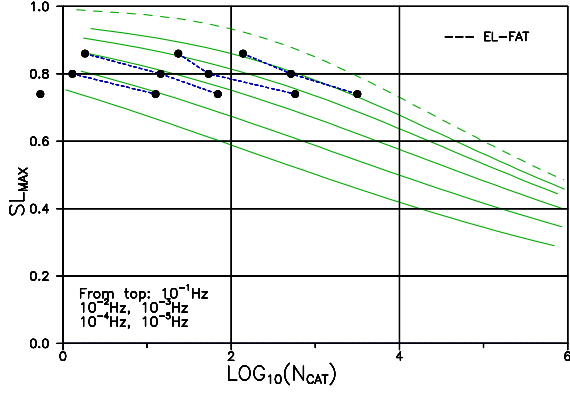


Figure 10. Fatigue of spruce compressed parallel to grain with $p = 0$. Experimental data from [7]. Elastic fatigue indicated is predicted lifetime at very high frequencies.

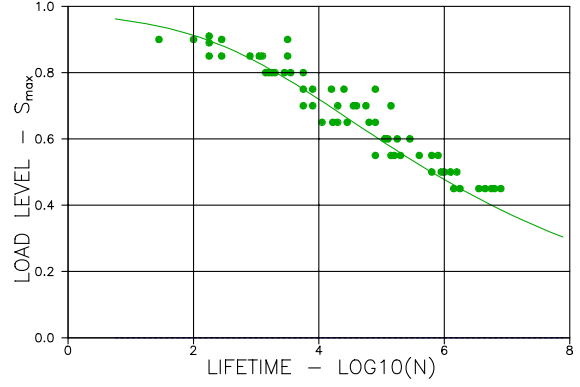


Figure 11. Lifetime of particleboards and hardboards loaded in tension and interlaminar shear with $(p,f) = (0.1, 15 \text{ Hz})$. Experimental data from [8,9].

Design graphs

It is observed from the master graphs shown in Figures 8 and 9 that lifetime can practically be described as elastic fatigue at non-dimensional load frequencies $f^*\tau > 10^5$ – and as deadload lifetime at frequencies $f^*\tau < 10$. In a transition area $10 < f^*\tau < 10^5$ both creep and elastic fatigue mechanisms are active. Easy safe estimates for load ratios, $p < 0.5$, can be made as shown in Equation 5 and demonstrated in Figures 12 and 13, (for higher load ratios the transition area has to be shifted to the right [1]). So-called fatigue parameters $(C,M) = (3,9)$ are used throughout the paper.

Elastic lifetime analysis:	$N_{CAT} = \frac{1}{G S_{LMAX}^2} \left[\frac{1 - S_{LMAX}^{M-2}}{(M-2) S_{LMAX}^{M-2}} - \frac{1 - S_{LMAX}^{M-4}}{(M-4) S_{LMAX}^{M-4}} \right] \quad \text{with } G = \frac{CFL^2}{13} \left[\frac{1-p^2}{2} \right]^M \quad (4)$ $t_{CAT} = N_{CAT} * T = N_{CAT} / f$
Viscoelastic lifetime analysis for $p < 0.5$	$\begin{cases} \text{dead load (Eq. 2) when } f\tau < 10 \\ \text{elastic fatigue (Eq. 4) when } f\tau > 10^5 \\ \text{straigh line log-log interpolation when } 10 < f\tau < 10^5 \end{cases} \quad (5)$

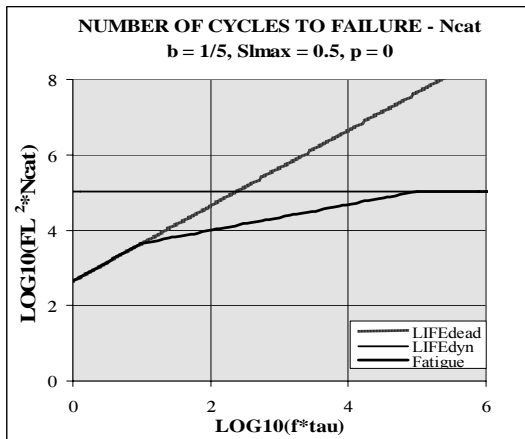


Figure 12. Non-dimensional presentation of number of cycles to failure (lower graphs). Frequency of loading is f .

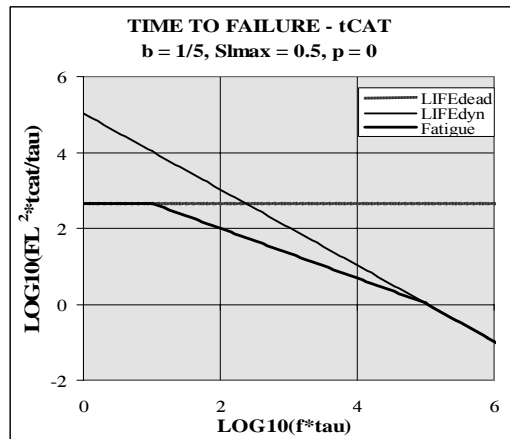


Figure 13. Non-dimensional presentation of time to failure (lower graphs). Frequency of loading is f .

3. LIFETIME AT VARIABLE MOISTURE

3.1 Generalized creep

Moisture variation and distribution

The moisture distribution in a cross-section of a wood beam is described with the following expressions suggested in [10] with α being a so-called moisture flow relaxation time. u_S and u_C are moisture content on the surface and in the middle part of a cross-section respectively.

$$\left. \begin{array}{l} \text{Moisture on surface of cross-section: } u_S = u_S(t) \\ \text{Moisture in middle parts of cross-section: } u_C = u_C(t) \end{array} \right\} \frac{du_C}{dt} = \frac{u_S - u_C}{\alpha} \quad (6)$$

$$\left. \begin{array}{l} \text{general: } \Delta u_{C(n)} = \frac{1}{\alpha} (u_{S(n)} - u_{C(n)}) \Delta t_{(n)} \quad ; \quad u_{C(n)} = u_{C(n-1)} + \Delta u_{C(n)} \\ \text{harmonic: } \begin{cases} u_S = u_{AV} + \Delta u_S \sin(\omega t) \Rightarrow u_C = u_{AV} + \Delta u_C \sin(\omega t - \delta) \\ \text{with } \omega = \frac{2\pi}{T}, \quad \Delta u_C = \frac{\Delta u_S}{\sqrt{1 + (\alpha\omega)^2}} \quad \text{and} \quad \delta = \arctan(\alpha\omega) \end{cases} \\ \text{constant: } u_C = u_S = u \end{array} \right\} \quad (7)$$

The moisture history used by Hoffmeyer in his lifetime experiments [5,6] has been simulated as shown in Figure 14 using the following parameters: Moisture loading: $u_{AV} = 15.5\%$, $\Delta u_S = 4.5\%$, $T = 56$ days. Moisture relaxation time: $\alpha = 5$ days.

Creep

The hypothesis is suggested in [10] that creep of wood subjected to a variable moisture history can be expressed by the following modified Power-law expression where K is a so-called moisture modification factor.

$$\left. \begin{array}{l} \text{In general:} \\ \frac{dC}{dt} = \frac{b}{t} \left(\frac{t}{\tau} \right)^b \quad \text{with relaxation time } \tau = \tau_{15} * 10^{[15 - (u_C + u_S)/2]/10 - ABS(u_C - u_S)/K} \\ \Rightarrow C \cong 1 + \left(\frac{t}{\tau_{REG}} \right)^b \quad \text{with relaxation time } \tau_{REG} \text{ determined by regression} \end{array} \right\} \quad (8)$$

The creep rate suggested is the same, which applies for the Power-law expression in Equation 1 – with time dependent relaxation time, however. For harmonic moisture variation the Power-Law creep expression determined by the latter expression in Equation 8 has a high fit quality to the creep function determined by the former expression. Thus, for such variations the conclusion can be made that the concept of Power-Law creep can be kept with a modified relaxation time τ_{REG} .

The creep functions shown in Figure 15 have been predicted according to Equation 8. The basic moisture histories assumed are those used by Hoffmeyer [5,6]. A moisture modification factor of $K = 2$ has been estimated. At $u = 11\%$, 20% , and variable $11-20\%$ relaxation times of $\tau = 25.4$ days, $\tau = 3.2$ days, and $\tau_{REG} = 0.85$ day respectively were predicted by Equations 7 and 8.

Remarks: It is noticed that Equation 8 predicts creep to increase with $\text{abs}(u_C - u_S)$ as a ‘driving force’ – and that Equations 1 and 8 become identical when moisture conditions are constant. The creep functions predicted (see Figure 15) consider real creep relevant for viscoelastic analysis. They represent smoothened, averaged mechano-sorptive creep functions as this phenomenon is observed in e.g. [5,11,12,13,14].

It is recognized that the moisture distribution model described above is rather crude, and has to be refined in further research. In the present paper, however, it fulfills its purpose: To demonstrate how moisture variations provoke increasing creep of wood – and decreasing lifetime. The model contains two parameters which have to be justified experimentally: The moisture flow relaxation time, α , and the moisture modification factor, K .

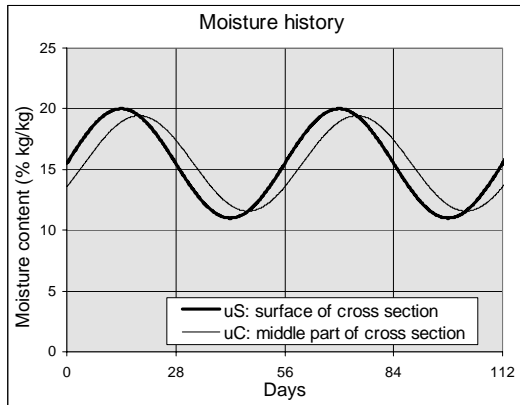


Figure 14. Sinus description of surface moisture variation $u_{MIN} - u_{MAX} = 11 \leftrightarrow 20\%$ used by P. Hoffmeyer [5,6].

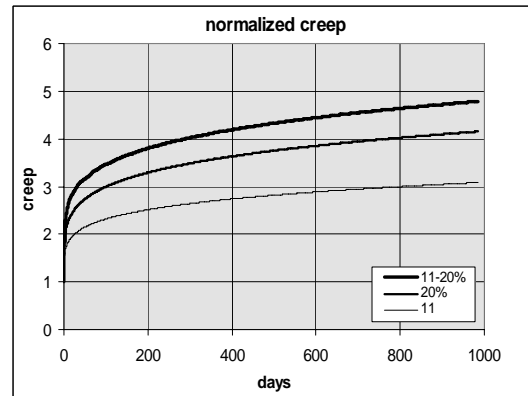


Figure 15. Predicted normalized creep (in damaged areas) for constant and variable moisture histories used in [5,6].

Generalization of analysis with respect to moisture

The observation made in Section 3.1 with respect to Power-Law descriptions is very important in the analysis of wood behavior as influenced by moisture variations: It means that the analysis of wood properties based on constant moisture content can be generalized to apply also for harmonically varying ambient moisture conditions. Examples are demonstrated in the following sections.

3.2 Constant load

Lifetime Equation 3 ($b = 1/5$) has been used to ‘predict’ the varying moisture experimental data obtained by Hoffmeyer in [5,6]. The results are shown in Figure 16 with a relaxation time of $\tau = 0.85$ day determined as described in Equation 8. Consistent residual strength data predicted by the second term in Equation 2 are presented in Figure 17.

3.3 Load history versus moisture history

The simultaneous agreement between theoretical predictions and the experimental results obtained by Hoffmeyer, see Figures 4, 5, and 16, for different moisture histories supports the idea that the basic damage mechanism (propagating cracks) ‘invented’ to explain the lifetime behavior of wood subjected to constant moisture conditions – applies also at variable moisture conditions with relaxation time modified as suggested in Equations 7 and 8.

This generalization can be extended to apply also for variable loads. In principles the creep mechanisms act in similar ways in theories developed for constant and variable loads [1].

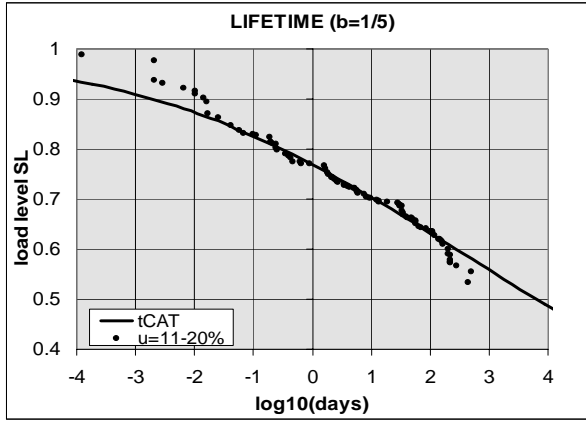


Figure 16. $FL = 0.25$; $\tau = 0.85$ days. $u = 11 \leftrightarrow 20\%$. Experimental data: P. Hoffmeyer [5,6].

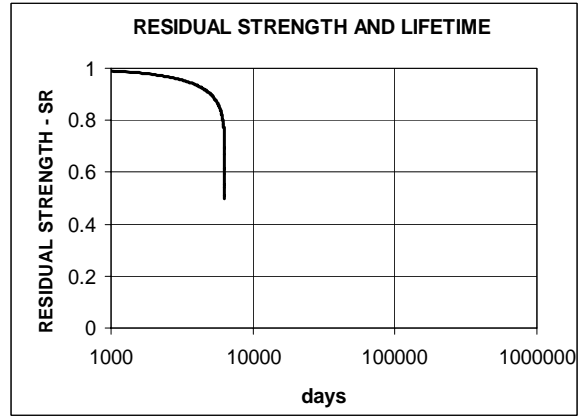


Figure 17. Residual strength and lifetime of wood ($FL = 0.25$). Load level is $SL = 0.5$. Power-Law creep with relaxation time, $\tau = 0.85$ days ($11 \leftrightarrow 20\%$), and a creep power of $b=1/5$.

3.4 Variable load (fatigue)

The observations made in Section 3.3 are now utilized to predict fatigue strength of wood subjected to both variable load and variable moisture. Some results of such analysis are presented in Figures 18 – 21.

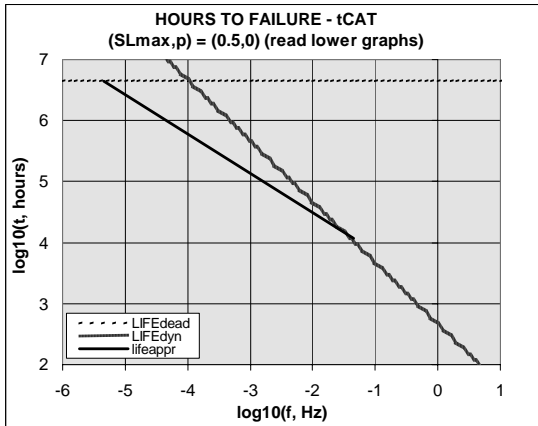


Figure 18. Predicted time to fatigue failure. $FL=0.25$, $u \approx 11\%$.

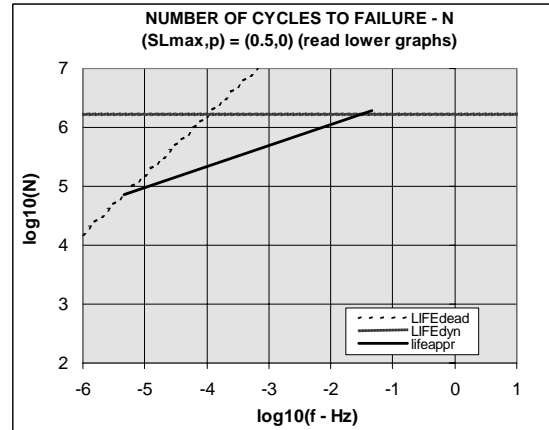


Figure 19. Predicted number of load-cycles to fatigue failure. $FL=0.25$, $u \approx 11\%$.

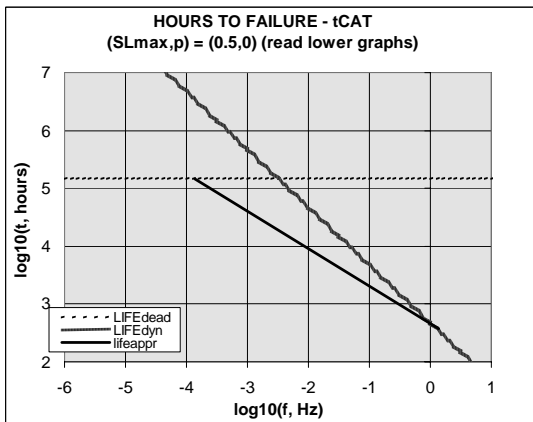


Figure 20. Predicted time to fatigue failure. $FL=0.25$, variable $u = 11-20\%$

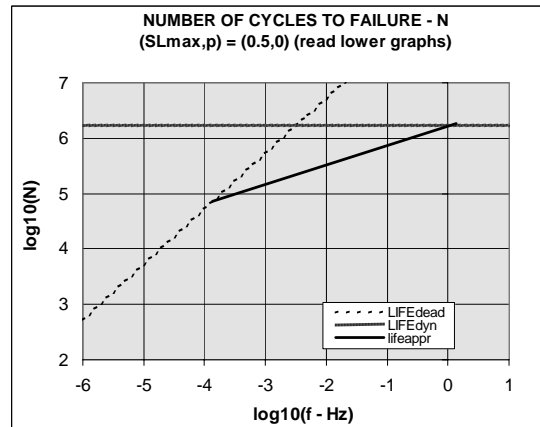


Figure 21. Predicted number of load cycles to fatigue failure. $FL=0.25$, variable $u = 11-20\%$

4. FINAL REMARKS

It seems logical to the author that the failure mechanism (damages) in wood stays practically independent of moisture content – leaving differences in strength behavior to be the results of moisture induced changes in viscoelastic behavior. The results presented in this paper justify this concept – and support the idea, outlined in the introductory section, of establishing a simple design procedure based on a simple basic model with the fewest possible parameters. These remarks are consistent with the observations made in Section 3.3.

Furthermore, it seems logical to generalize damage-based solutions to apply also when different loading modes are considered, such as in: Torsion, various slopes of lamellae in Glu-lam, and various joint systems.

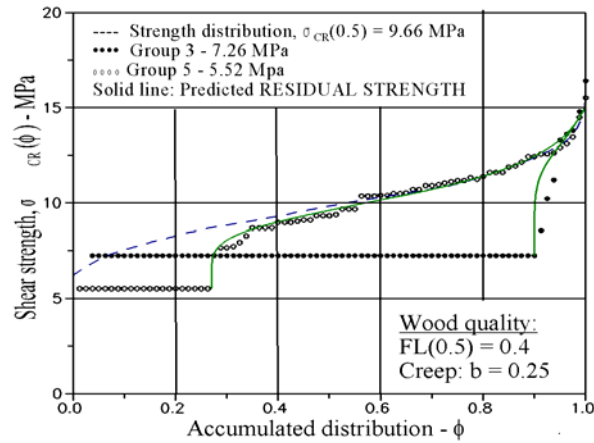


Figure 22. Residual strength distribution in duration of torsional shear load experiments on small clear wood specimens. Experimental data [15]. Horizontal string represents no residual strength.

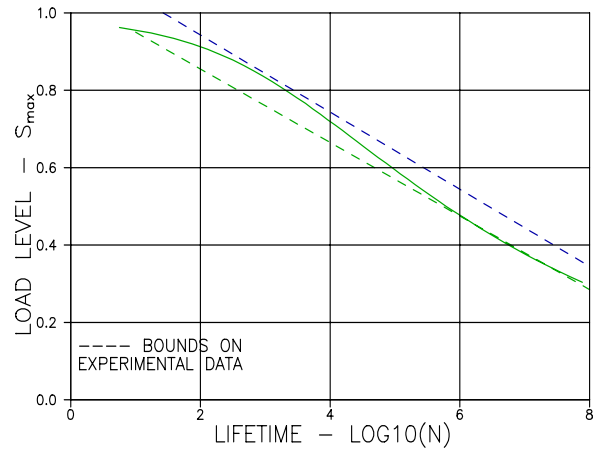


Figure 23. Lifetime of Doug-Fir finger joints loaded in tension \perp grain with $(p,f) = (0.1, 15 \text{ Hz})$. Experimental data from [16,17].

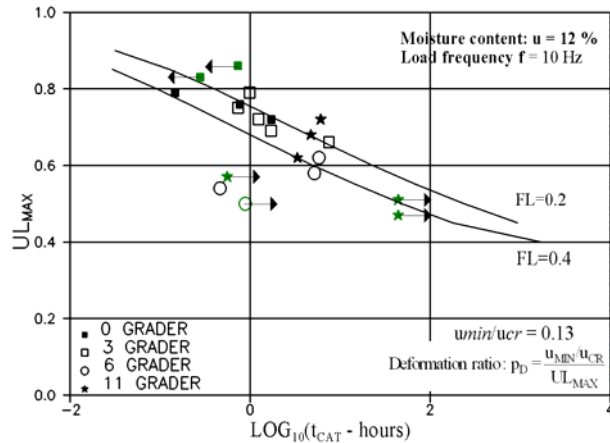


Figure 24. Glu-Lam beam. Deformation control. Single sided bending. $(b,\tau) = (0.25 \text{ 5 days})$. ‘Grader’ is angle between beam direction and lamella. Experimental data reported in [18].

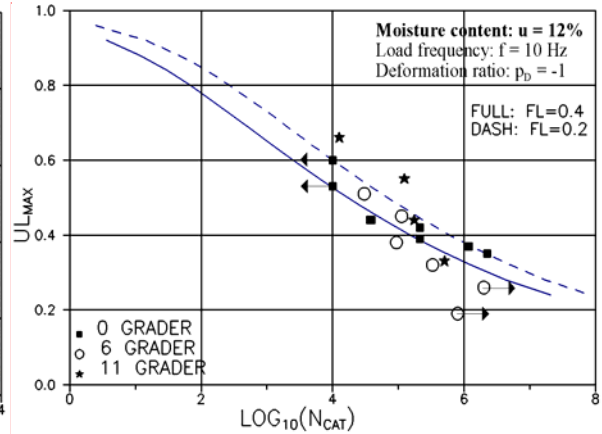


Figure 25. Glu-Lam beam. Deformation control. Double sided bending. $(b,\tau) = (0.25 \text{ 5 days})$. ‘Grader’ is angle between beam direction and lamella. Experimental data reported in [18].

Support to this idea can be found in the DVM-theory: We reproduce from [2]: The advantage of the DVM-theory to operate in general with non-dimensional load ($SL = \sigma/\sigma_{CR}$) and non-dimensional materials quality ($FL = \sigma_{CR}/\sigma_L$) means that these terms can often be evaluated in a generali-

zed way involving forces and structural dimensions. For example, when load is a normal tensile force N on a cross-section we may consider N as a generalized load. Load level is $SL = N/N_{CR}$ and materials quality is $FL = N_{CR}/N_L$ where N_{CR} and N_L are forces which produce short-time failure and theoretical failure (no cracks), respectively. It is shown in [2] that this deduction applies for the damage model applied (Dugdale crack) for practically any loading mode.

The generalizing suggestions made are supported by comparing theoretical DVM-results with test results reported by Spencer/Madsen [15], Bohannon/Kanvik [16], MacNatt [17], and Nielsen [18] - see Figures 22 – 25.

It has been demonstrated in this paper that the simplifications made of design for lifetime and re-cycle strength of wood is a logical consequence of *not changing wood structural models* every time new problems are met. Other analytical procedures might also benefit from such a simplification concept: Reliability studies may become more ‘reliable’ by knowing that property distributions can be related. This feature is illustrated in Figures 26 and 27 reproduced from [19].

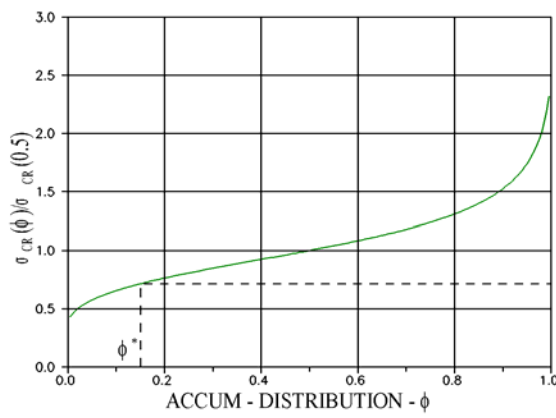


Figure 26. Strength distribution. Reproduced from [19].

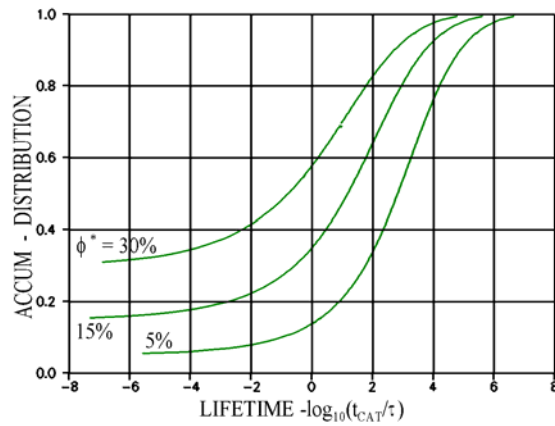


Figure 27. Lifetime distribution associated with the strength distribution in Figure 26. Load is $\sigma = \sigma_{CR}(\varphi^*)$. $FL = FL(\varphi^* = 0.5) = 0.2$. Reproduced from [19].

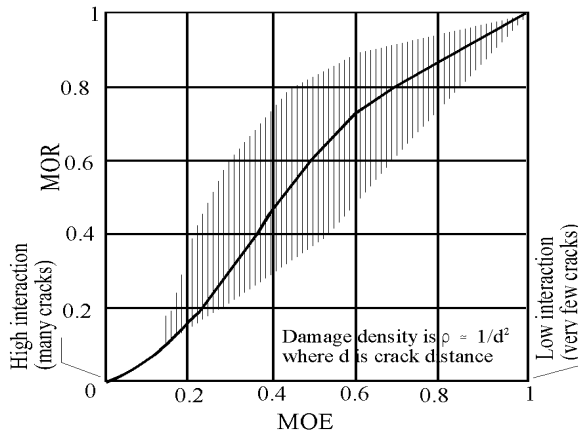


Figure 28. MOE-MOR relation for wood. Shaded area covers roughly the data for 1200 oak and cottonwood beams presented in [22]. Roughly reproduced from, [21, Figure 9].

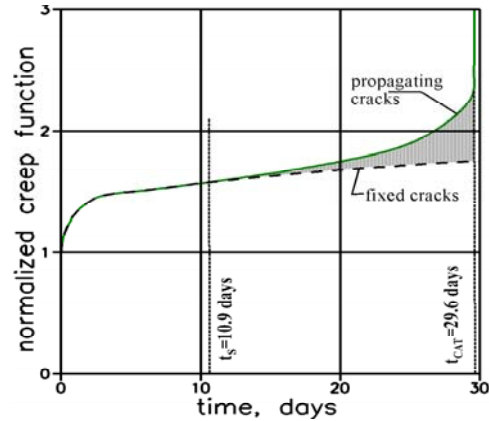


Figure 29. Creep function for clear wood. Multi-crack model. The shaded area represents the effect of running cracks. Roughly reproduced from, [20, Figure 7].

Finally, the author is presently investigating the deformational behavior of wood caused by damage mechanisms - also from the viewpoint of applying existing material/structural mo-

dels. For deformations the simplification concept mentioned above is slightly more complicated. Deformation is a consequence of the joint behavior of many damages – while failure primarily is a consequence of one major defect. The results of the investigation are not yet fully presentable – except for the examples, Figures 28 and 29, already presented in [20,21] with experimental MOE-MOR data from [22] (Modulus Of Elasticity - Modulus Of Rupture).

LIST OF SYMBOLS

The symbols most frequently used in this paper are listed below. The list does not include local symbols used only in intermediate results. The extensive use of normalized quantities such as load level and strength level should be noticed.

Load and strength

Load in general	σ
Strength (reference)	σ_{CR}
Theoretical strength	σ_I
Strength level	$FL = \sigma_{CR}/\sigma_I$
Load level	$SL = \sigma/\sigma_{CR}$
Minimum load	σ_{MIN}
Minimum load level	$SL_{MIN} = \sigma_{MIN}/\sigma_{CR}$
Maximum load	σ_{MAX}
Maximum load level	$SL_{MAX} = \sigma_{MAX}/\sigma_{CR}$
Load ratio	$p = \sigma_{MIN}/\sigma_{MAX} = SL_{MIN}/SL_{MAX}$
Residual strength (re-cycle strength)	$S_R = \sigma_{CR}(t)/\sigma_{CR}$

Deformational load

Deformation	u
Deformation at fracture	u_{CR}
Deformation level	$UL = u/u_{CR}$
Minimum deformation	u_{MIN}
Maximum deformation	u_{MAX}
Minimum deformation level	$UL_{MIN} = u_{MIN}/u_{CR}$
Maximum deformation level	$UL_{MAX} = u_{MAX}/u_{CR}$
Deformation ratio	$p_D = u_{MIN}/u_{MAX} = UL_{MIN}/UL_{MAX}$

Deformation

Crack length	l
Initial crack length (reference)	l_0
Damage ratio (or just damage)	$\kappa = l/l_0$
Damage density	ρ , number of damages per volume or area unit

Fatigue parameters

Damage rate constant	$C \approx 3$
Damage rate power	$M \approx 9$

Time and creep

Time in general	t
Relaxation time (or doubling time)	τ
Creep power	b
Young's modulus	E
Creep function	$c = (1 + (t/\tau)^b)/E$
Normalized creep function	$C = 1 + (t/\tau)^b$
Time shift parameter	$q = (0.5(1 + b)(2 + b))^{1/b}$

Lifetime and load cycles

Cycling time	T
Frequency (cyclic)	$f = 1/T$
Frequency (angular)	$\omega = 2\pi/T$

Lifetime	t_{CAT}
Number of load cycles to failure	$N_{CAT} = t_{CAT}/T = f^*t_{CAT}$
Moisture	
Surface moisture content	u_S
Moisture content in middle parts	u_C
Moisture flow relaxation time	α
Moisture modification factor	K

LITERATURE

- [1] Nielsen, L. Fuglsang: 'Lifetime and residual strength of wood subjected to static and variable load', Part I: 'Introduction and analysis', and Part II: 'Applications and design', Holz als Roh- und Werkstoff, 58(2000), 81-90 and 141-152.
- [2] *Idem*: "DVM-analysis of wood - Wood as a damaged viscoelastic material". In Borg Madsen: "Structural Behavior of Timber", Timber Engineering Ltd., North Vancouver, B.C., Canada 1992.
- [3] *Idem*: "Lifetime, Residual Strength, and Quality of Wood - and other viscoelastic materials". Holz als Roh- u. Werkstoff, 49(1991), 451-455.
- [4] *Idem*: 'Lifetime as related to materials quality – with special reference to wood', Report R-105(2004), Department of Civil Engineering, Technical University of Denmark.
- [5] Hoffmeyer, P.: Failure of wood as influenced by moisture and duration of load. Doctoral Dissertation. State University of New York, College of Environmental Science and Forestry, 1990.
- [6] *Idem*: Strength under Long-Term Loading. In Thelandersson, S. and Larsen, H.J. (Eds.): Timber Engineering. John Wiley & Sons, Ltd., 2003
- [7] Bach, L.: "Frequency-dependent fracture under pulsating loading". Build. Mat. Lab., Tech. Univ. Denmark, Tech. report 68, 1979, (presented at Forest Prod. Res. Society Annual Meeting 1975, Portland, Oregon, USA).
- [8] McNatt, J. D.: "Fatigue Properties of Three Particleboards in Tension and Interlaminar Shear". Forest Products Journ., 26(1976), 45 - 48.
- [9] *Idem*: "Design stresses for hardboard - effect of rate, duration, and repeated loading". Forest Products Journ., 20(1970), 53 - 60.
- [10] Nielsen, L. Fuglsang: "Power-Law creep of wood - moisture variation aspects", Conference of Int. Union of Forestry Research Organizations (IUFRO), Bordeaux - France, 17.-21. August 1992. Proc. (ed. Hoffmeyer, P.), Build. Mat. Lab., Tech. Univ. Denmark, 1993, pp 123-134.
- [11] Mohager, S: "Studies of creep in wood" (in Swedish), Thesis, The Royal Institute of Technology, Report TRITA-BYMA 1(1987).
- [12] Mårtensson, A.: "Mechanical behavior of wood exposed to humidity variations". Thesis, Report TVBK-1006, Lund Institute of Technology, Dept. Struct. Eng., Sweden 1992.
- [13] Toratti, T.: 'Creep of timber beams – models, experiments and applications', Conference of Int. Union of Forestry Research Organizations (IUFRO), Bordeaux - France, 17.-21. August 1992. Proc. (ed. Hoffmeyer, P.), Build. Mat. Lab., Tech. Univ. Denmark, 1993, 135 - 174.
- [14] Houska, M.: 'Mechano-sorptive effect of the different categories of spruce wood', International conference on wood-water relations, 16-17 June 19997, Copenhagen, Denmark, Proc. (ed. Hoffmeyer, P.) COST-E8: Dept. Civ. Eng., Tech. Univ. Denmark, 1993, 135 - 174.
- [15] Spencer, R.A. and Madsen, B.: "Duration of load tests for shear strength". Conference of Int. Union of Forestry Research Organizations (IUFRO), Xalapa, Mexico, December 1984. Proc., Build. Mat. Lab., Techn. Univ. Denmark 1985, 225 - 243.
- [16] Bohannon, B. and Kanvik, K.: "Fatigue Strength of Finger Joints". F.P.L., U.S.D.A., Rep. No. 114 (1969).
- [17] McNatt, J. D.: "Linear Regression of Fatigue Data". Wood Science, 11(1978), 39-41.
- [18] Nielsen, L. Fuglsang: 'Træs udmattelse – Prediction af træbjælkens levetid og reststyrke' (in Danish: 'Fatigue of Wood – Prediction of lifetime and residual strength for wooden beams'), Technical report LBM 294(1993), Building Materials Lab., Tech. Univ. of Denmark. Final analysis of experimental data obtained in Sub-

project 1.2 under the research programs ‘Advanced Materials based on Straw and Wood’ and ‘Fatigue of Glue-lam’, sponsored by the Ministry of Trade and Industry (1989) together with the Governmental Research Foundation (1988), Denmark.

[19] *Idem*: "Lifetime of wood as related to strength distribution", in "Reliability-Based Design on Engineered Wood Structures", (ed. J. Bodig), Kluwer Academic Publishers, Dordrecht, The Netherlands, 1992.

[20] *Idem*: ‘A lifetime analysis of cracked linear viscoelastic materials – with special reference to wood’, Conference of Int. Union of Forestry Research Organizations (IUFRO), Borås, Sweden, Maj 1982. Proc., Chalmers University of Technology, Dept. Struct. Eng. 1982, 151 – 178.

[21] *Idem*: ‘On the mechanical behavior of materials with interacting cracks’, Conference of Int. Union of Forestry Research Organizations (IUFRO), Borås, Sweden, Mai 1982. Proc., Chalmers University of Technology, Dept. Struct. Eng. 1982, 141 - 149.

[22] Walters, C.S. and Reiss, W.L.: ‘Predicting modulus of rupture from modulus of elasticity for small clear specimens of oak and cottonwood’, Forest Products Journal, 27(1977), 51.